

CAAP Quarterly Report

Date of Report: Jan 10, 2020

Prepared for: *U.S. DOT Pipeline and Hazardous Materials Safety Administration*

Contract Number: *693JK31950001CAAP*

Project Title: *Improved NDT Detection and Probabilistic Failure Prediction for Interacting Pipeline Anomalies*

Prepared by: *Vikas Srivastava and Sijun Niu*

Contact Information:

Vikas Srivastava, Ph.D.

Assistant Professor of Engineering

Brown University

184 Hope Street, Box D,

Providence, RI 02912

Email: vikas_srivastava@brown.edu

Phone: 401-863-2863

For quarterly period ending: *December 31st, 2019*

Business and Activity Section

(a) Contract Activity

No modifications were made to contract. No material purchase occurred in this quarter.

(b) Status Update of Past Quarter Activities

The project started this past quarter (Oct – Dec 2019). During this quarter, literature review on modeling and finite element simulations of ultrasonic wave propagation in solids and non-destructive testing (NDT) was performed. A finite element simulation methodology using for sound wave propagation in elastic solids with single anomaly was developed using commercially available Abaqus finite element software package. Early plane strain simulations were conducted using a commercial software package Abaqus and the results were analyzed. Results obtained agree reasonably well with expected outcomes. Further research into modeling, simulation and signal processing work will continue to optimize the simulation time to include more complex geometries and to reduce numerical simulation noise for enhanced NDT simulation based anomaly detection.

(c) Cost share activity

Partial support for 1 graduate student tuition were provided by Brown University School of Engineering as per the cost share agreement.

(d) Task 1: Numerical simulation study of ultrasonic test using finite element analysis

1. Background and Objectives in the 1st Quarter

1.1 Background

Current ultrasonic non-destructive testing methods of classification of defect types and sizes are limited due to uncertainties in detection and also due to interpretation from reliance on varying human expertise.^{[1][2]} Current trend in machine learning has proved useful in the application of ultrasonic NDT.^[3] We envision that a simulation based understanding of ultrasonic NDT process and a machine learning algorithm based automated methodology is expected to reduce uncertainties in anomaly detections.^[4] Lack of high volume of data due to high expense in experiments limits the development of the algorithm. At the current stage, a simulation-driven research is performed in order to evaluate physics of ultrasonic NDT methodology and also to be able to create a higher volume of data for training the neural network models.

1.2 Objectives in the 1st Quarter

We aimed to develop a finite element simulation methodology for ultrasonic NDT and to conduct early finite element simulations in which ultrasound travels through simple test geometries with the material properties same as steel pipelines. We aimed to study elliptical crack embedded at different locations in a steel plate.

2. Experimental Program in the 1st Quarter

2.1 Experimental design

No experiments were required or performed in the 1st quarter.

2.2 Computational setup

Computations were conducted on an existing workstation.

We studied finite element based numerical simulation requirements for sound wave propagation in steel. For our we chose an ultrasound wave of 5 MHz frequency with a wavelength of ~ 1.2 mm. We obtained that 10-15 meshes per wavelength provided a numerically stable practical element size. We also considered the Courant-Friedrichs-Lewy (CFL) condition and obtained the maximum allowable time step for our simulations.

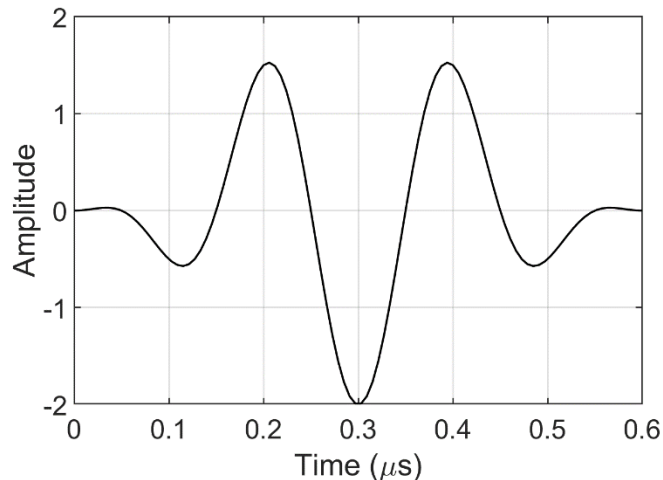


Figure 1. 5MHz, 3 period raised-cosine type pulse signal used in the simulations.

A steel plate geometry with width 60 mm and thickness 20 mm was used in our simulations. 5 mm linear length at the bottom surface was taken as ultrasound signal exciter. Longitudinal wave which is most commonly used was monitored inside the steel plate and at the receiver. Other waveform such as shear wave and Lamb wave are sometimes used for certain applications.^{[5][6]} A short 5 mm long ultrasound signal exciter with 5 MHz raised-cosine type waveform as shown in Figure 1 was applied as boundary condition to the bottom edge of the plate thickness.^{[7][8]} Anomalies in the form of elliptical cracks were embedded in the steel plate and studied. We conducted dynamic numerical simulations in Abaqus/Explicit and analyzed the displacement history profile at the selected point receiver locations. Our analysis of the preliminary simulation results show that we are able to detect signal reflected from the embedded anomalies present in the plate.

Results and Discussions

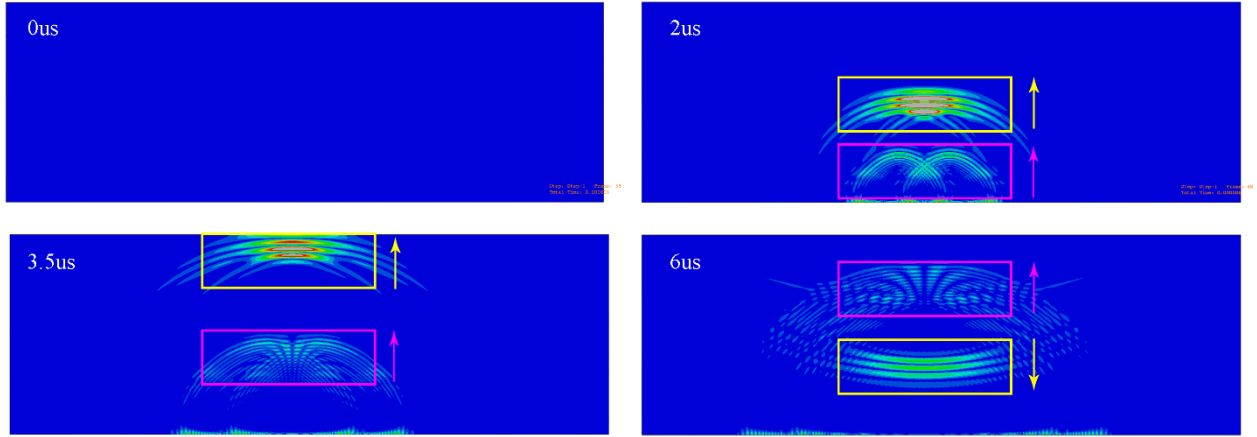


Figure 2. Simulation based wave propagation and displacement results in a plate (benchmark case without anomaly) subjected to ultrasound wave excitation at the bottom edge

Figure 2 shows the magnitude of displacement inside a plate (without anomaly as a benchmark case) at four different time frames of 0 μ s, 2 μ s, 3.5 μ s and 6 μ s from top left to bottom right. The yellow box indicates the longitudinal wave, the pink box indicates the shear wave, and the arrows mark the directions of the wave travel. The longitudinal and shear wave are both clearly visible in the simulation where the shear wave is traveling at approximately half of the speed of longitudinal wave, which agrees well with the theoretical prediction. In the bottom right panel, the longitudinal wave has been reflected from the other edge and is traveling in the reverse direction.

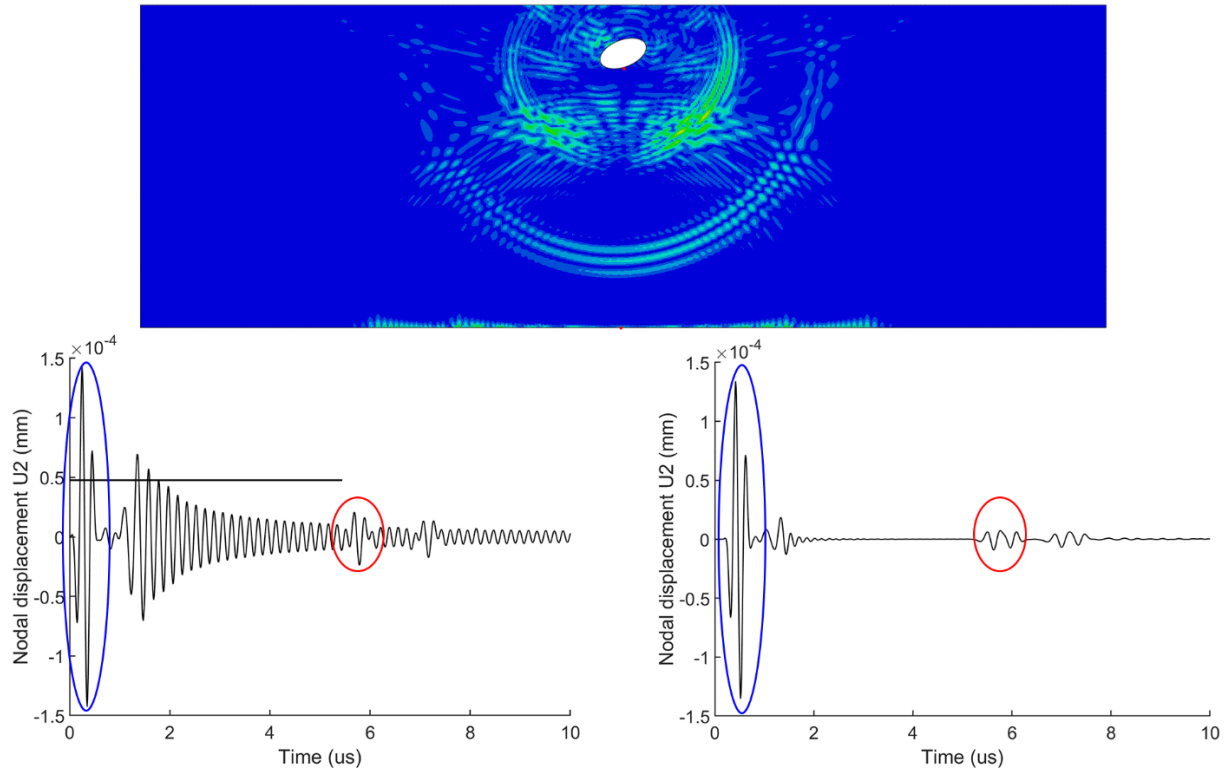


Figure 3. *Simulation of wave propagation in a plate with elliptical crack present. Time history of vertical nodal displacement at and near the bottom edge indicates the detection of the crack*

As shown in Figure 3, we investigate the ultrasonic wave signal inside a plate with an embedded elliptical crack. The pulse is assumed to be emitted right under the crack. The upper panel shows the displacement field inside the plate at $3.9 \mu\text{s}$, and the bottom panels are the time history of vertical nodal displacement of two nodes. The input signal, and the received signal reflected back from the elliptical crack are marked with blue and red ellipses, respectively. Although a strong pattern of oscillation or a background noise is visible in the simulation, the reflected signal from the embedded crack is still distinct. In the bottom left, the signal receptor node is selected to be on the boundary. The black solid horizontal line indicates the theoretical prediction of the time needed for the wave to travel and be reflected from the elliptical crack boundary. Given the material properties, the theoretical sound speed is 5913 m/s and the total time needed to pick up the reflected signal is twice the distance to the crack divided by the sound speed which turns out to be $5.41 \mu\text{s}$. As shown the simulation result matches well with the theoretical prediction.

The presence of noise makes the ultrasound testing result more difficult to interpret and needs further investigation. We found that at approximately 1 mm above the receiver edge, the signal appears to be clear without any noise (shown in right bottom panel in Figure 3). We deduce that the noise occurs due to the free boundary at the bottom of the plate which needs to further studied in order to reduce/remove the unwanted noise. Possible signal processing techniques will be utilized including cross-correlation, wavelet transform and Hilbert-Huang transform.^[9]

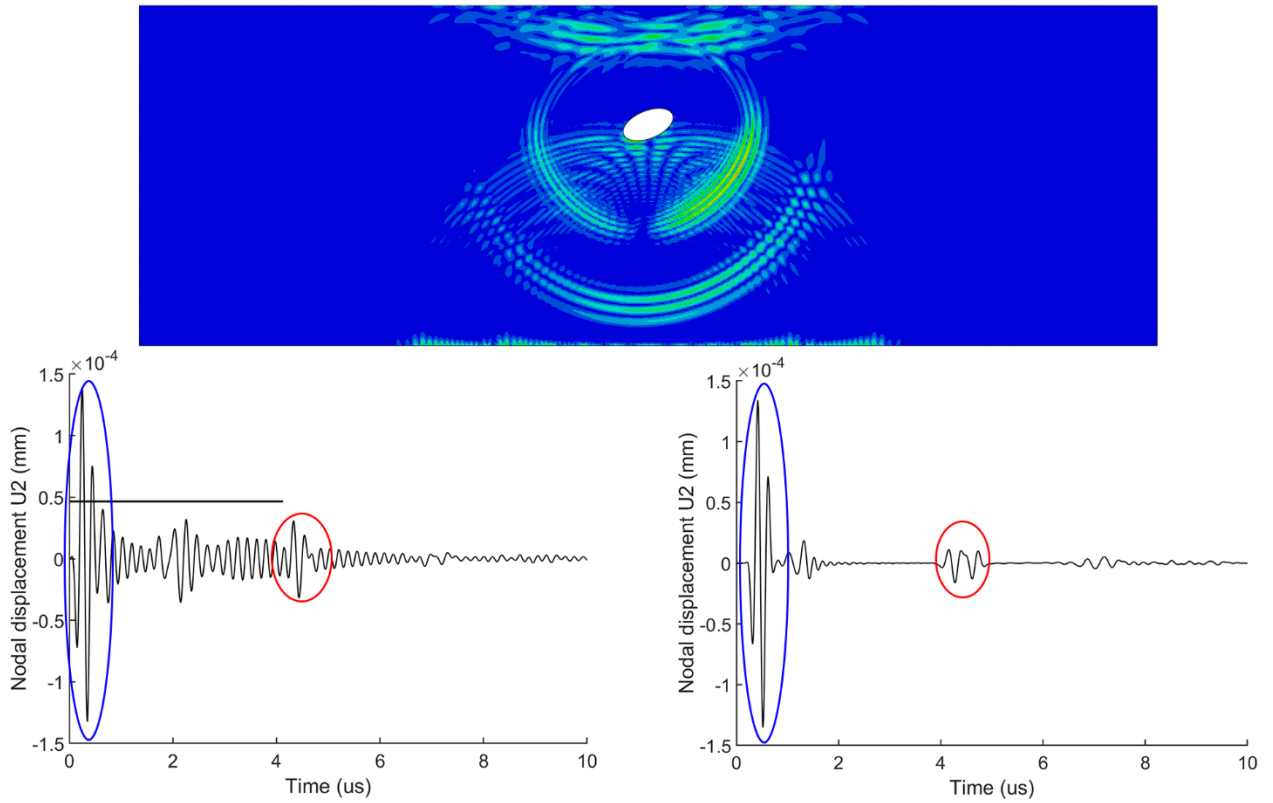


Figure 4. *Simulation of wave propagation in a plate with elliptical crack present in a different location. Time history of vertical nodal displacement at and near the bottom edge indicates the detection of the crack*

Figure 4 is organized the same as Figure 3, except in this case, the crack is closer to the bottom boundary. The displacement field in the upper panel is shown for $3.9 \mu\text{s}$. A comparison to figure 3 shows that the reflected longitudinal wave is closer to the bottom boundary in this case due to closer proximity of the crack from the bottom edge. The time signal shown in the bottom panels of Figure 4, showed that the simulation results matched with the expected prediction.

Future work

In the coming quarter, we will continue to investigate the ultrasound NDT simulations in a systematic way for additional scenarios. We will study the surfaces waves and undesired signal noise generated at the ultrasound exciting plate edge with a goal to remove or minimize the undesired signal noise. We have successfully implemented two dimensional plane strain condition simulation methodology; in the near future we will extend this simulation capability for three dimensional geometries as well. We also plan to purchase an ultrasound NDT detector and conduct preliminary tests.

Extending beyond the next quarter, we aim to establish a machine learning algorithm using neural network. Once the simulation methodology is well established, our goal will be to detect/interpret anomaly size in addition to its location using machine learning. The set of numerical simulation data will be randomly distributed into two groups, namely a training group and a validation group. Both groups are necessary for calibrating and validating the reliability of the algorithm. We will also develop probabilistic failure models for pipelines with anomalies.

References

- [1] Y. Yao, S.-T. E. Tung, and B. Glastic, “Crack detection and characterization techniques—An overview,” *Struct. Control Heal. Monit.*, vol. 21, no. May 2011, pp. 1387–1413, 2011.
- [2] A. A. Carvalho, J. M. A. Rebello, M. P. V. Souza, L. V. S. Sagrilo, and S. D. Soares, “Reliability of non-destructive test techniques in the inspection of pipelines used in the oil industry,” *International Journal of Pressure Vessels and Piping*, vol. 85, no. 11. pp. 745–751, 2008.
- [3] S. Sambath, P. Nagaraj and N.Selvakumar, “Automatic Defect Classification in Ultrasonic NDT Using Artificial Intelligence”, *J Nondestruct Eval* (2011) 30: 20–28
- [4] F.Casadei, J.J.Rimoli and M.Ruzzene, “Multiscale finite element analysis of elastic wave scattering from localized defects”, *Finite Elements in Analysis and Design* 88 (2014) 1–15
- [5] Morten Voß et al., “Numerical simulation of the propagation of Lamb waves and their interaction with defects in C-FRP laminates for non-destructive testing”, *Advanced Composite Materials*, 2019
- [6] S. Yashiro, J. Takatsubo and N. Toyama, “An NDT technique for composite structures using visualized Lamb-wave propagation”, *Composites Science and Technology* 67 (2007) 3202–3208
- [7] H. Chen, K. Sun, C. Ke, and Y. Shang, “Simulation of ultrasonic testing technique by finite element method,” in *Proceedings of IEEE 2012 Prognostics and System Health Management Conference, PHM-2012*, 2012.
- [8] R. Ludwig and W. Lord. “Developments in the finite element modelling of ultrasonic NDT phenomena”. *Review of Progress in Quantitative Nondestructive Evaluation*, 5A, American Institute of Physics, 73-81, 1986.
- [9] Kumar Anubhav Tiwari, Renaldas Raisutis and Vykintas Samaitis, “Hybrid Signal Processing Technique to Improve the Defect Estimation in Ultrasonic Non-Destructive Testing of Composite Structures”, *Sensors* 2017, 17, 2858; doi:10.3390/s17122858